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HAWAII DEPARTMENT OF HEALTH EVALUATION OF GROUNDWATER FLOW PATHS IN THE MOANALUA, RED HILL, AND HALAWA REGIONS; REVISION 2

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Abstract

Understanding how groundwater flows beneath the Navy's Red Hill Bulk Fuel Storage Facility (Facility) is critical to evaluating the risk to drinking water aquifers and sources. The Hawaii Department of Health (DOH), Source Water Protection Program (SWPP) merged data collected by the Navy with other data sets to evaluate the most likely travel trajectories for groundwater flowing beneath the 20-12.5 million gallon underground fuel storage tanks (USTs) within the Facility. Our conclusion based on measured groundwater gradients and the geometry of hydrogeologic barriers is that the primary direction of shallow groundwater beneath the upper part of the Facility is toward the northwest. The conclusions of this report stop short of evaluating the risk that fuel releases from the Facility pose to any particular drinking water source, but is the first, critical, step to more concisely defining the actual probability that a fuel release from the Facility could impact a public drinking water source.

Introduction

The Hawaii Department of Health (DOH) as one of the parties to the *Administrative Order on Consent In the matter of Red Hill Bulk Fuel Storage Facility* (AOC) reviews the products provided by the Navy to fulfill their obligations under the AOC. One of the tasks of the AOC Statement of Work (SOW) is to assess the risk the Red Hill Bulk Fuel Storage Facility (Facility) poses to drinking water aquifers and public drinking water sources that draw from those aquifers. The DOH Safe Drinking Water Branch Source Water Protection Program (SWPP) performs a similar function for all public drinking water sources for the State of Hawaii. Also, the methodology used by SWPP to assess the risk of contamination to public drinking water sources is similar to that which the Navy is using to fulfill their obligations under the AOC. Due to the similarity in functions with regard to risk posed to drinking water resources, the SWPP is ideally positioned to review the Navy's technical deliveries and provide technical insight that can be critical to understanding the risk that the Facility poses to nearby drinking water sources.

In July and August, 2018, as part of the ongoing investigation of the Red Hill Bulk Fuel Storage Facility, the Navy presented to the Regulatory Agency Subject Matter Experts (SME) a draft Conceptual Site Model (CSM) (DON, 2018a) and a preliminary groundwater flow model (DON, 2018b) with which to assess the risks posed by the Facility to groundwater and public drinking water sources. During discussions of these models, the SMEs raised a number of concerns with the assumptions incorporated into both models, assertions that have been made about the formation properties and flow trajectories that have not been validated by field data. In some cases, corrections have been made to better address the SME's concerns, but in others, substantial differences of opinion remain that will significantly affect the computed potential risks posed by future releases from these tanks for drinking water sources in the region around the Red Hill Bulk Fuel Storage Facility.

The Navy is expected to submit the Groundwater Flow Model Report in October, 2019, as required by the AOC, which should include responsive changes to SME comments and discussions. Since changes to the CSM and groundwater flow model are in progress by the Navy team, this memo is intended to convey the important outstanding issues that need resolution in both the CSM and numerical groundwater model. Below are discussed the major points of disagreement between the Regulator SMEs with the Navy's current CSM and Groundwater Flow Model. Summarized briefly they include:

- The disparity between the measured and modeled groundwater gradient along the axis of Red Hill Ridge and its implications for a reliable CSM and numerical groundwater flow model
- The absence of supporting field data for the CSM-assumed primary groundwater flow direction toward the southwest and away from Halawa Shaft (one of the key receptors of concern); and
- Lack of consideration of groundwater flow toward the northwest without providing a compelling rationale.

What follows is an analysis of the groundwater flow direction hypothesized by the Navy, the data and hypotheses the Navy uses to support that flow direction, and DOH's preliminary evaluation of the controls on groundwater flow direction in the Moanalua, Red Hill, Halawa regions.

Red Hill Oversight

The Red Hill AOC SOW Section 7 requires the Navy to characterize the flow of groundwater around the Facility. To comply with this requirement the Navy must submit a groundwater flow to the DOH and the U.S. Environmental Protection Agency (EPA), the AOC regulatory agencies. Due to model the expertise of the Safe Drinking Water Branch, Source Water Protection Program (SWPP) in Hawaii regional groundwater flow and contamination risk assessments, and groundwater modeling, this program has been tasked by DOH to be the primary technical reviewer for the Navy's groundwater flow deliverables under Section 7. As described below, an independent review of the risk posed by the Facility to public drinking water sources is also within the mission of the SWPP.

Source Water Protection Program

The 1996 Safe Drinking Water Act Amendments established a new Section 1453 for source water quality assessments. These assessments delineate the boundaries of areas providing source waters for public water systems, and identity the origins of regulated and unregulated contaminants in the delineated area to determine the susceptibility of public water systems to contamination. This function is performed for all public drinking water systems by the SWPP. Specifically for the Red Hill AOC, the SWPP is doing assessments to evaluate susceptibility of public drinking water sources to contamination from the Facility.

Presentation of DOH Understanding of Groundwater Flow Paths in the Moanalua, Red Hill, and Halawa Regions

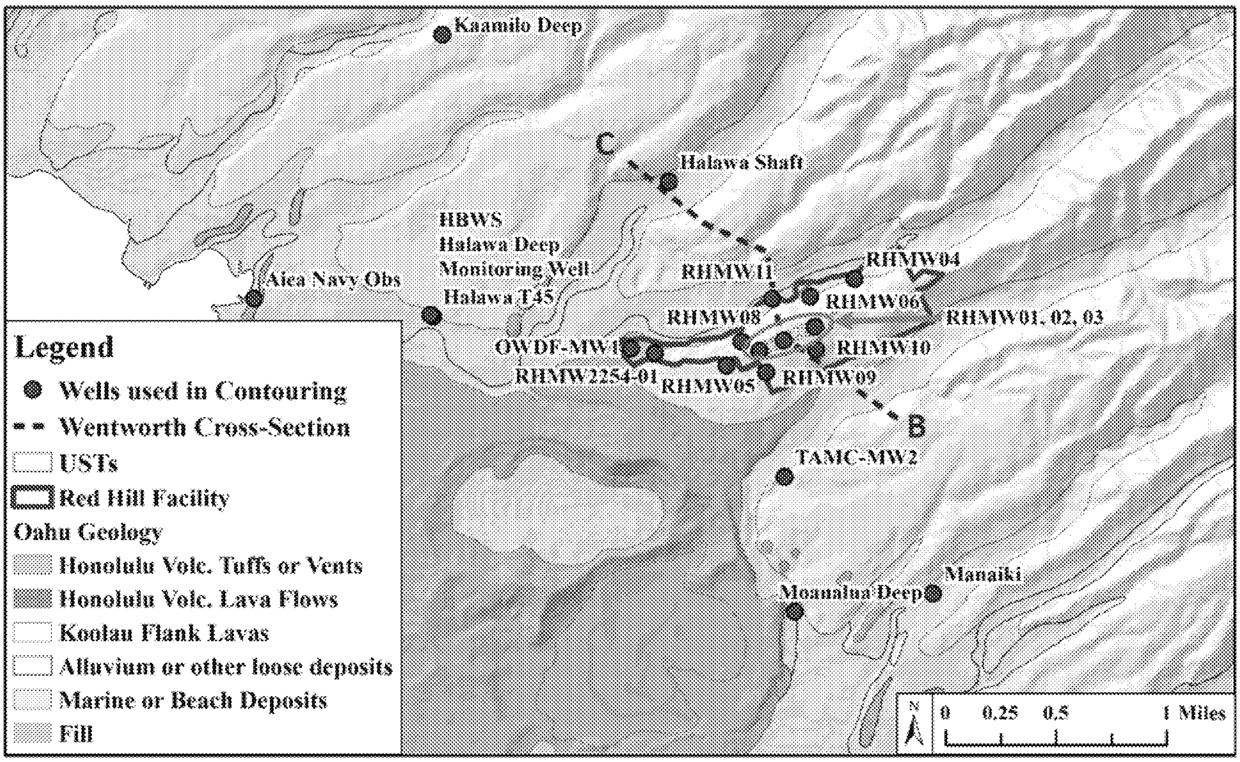

Figure 1. This figure shows the location of the observation wells used to contour the regional water levels. Also shown is a generalized geology of the Moanalua/Red Hill/Halawa region and the trace of the Wentworth (1942) cross-section.

Groundwater Elevations

Figure 1 shows the location of the groundwater elevation observation points used in this evaluation. This includes the wells of the Red Hill Groundwater Monitoring Network (RHGWMN), Honolulu Board of Water Supply (HBWS) observation and deep monitoring wells, and other Navy, Army, and US Geological Survey (USGS) observation wells.

Figure 2 graphs the groundwater elevations of the wells going down the axis of the Red Hill Ridge that include RHMW03, RHMW02, RHMW01, and RHMW05. These water levels are plotted versus distance in miles from the east end of the Red Hill Shaft infiltration gallery. The groundwater elevations for four different pumping conditions are shown and compared to results of the Navy's preliminary Red Hill base groundwater flow model presented in the Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (DON, 2018b).

- "Nov-16" are those water levels measured November 18, 2016 during the snapshot synoptic water level survey taken by the Navy, USGS, Commission on Water Resources Management (CWRM), and HBWS. The data are taken from Figure 6-4 of DON, 2018a.
- "RHS Off" represents the water levels measured January 15, 2018 after the Red Hill Shaft had been off for about 5 days (Figure 6-8 of DON, 2018a).
- "RHS Normal" represents the water levels measured on February 19, 2018 when both the Red Hill Shaft and the Halawa Shaft are pumping at their normal rates (Figure 6-12 of DON, 2018a).
- "RHS Max" represents the water levels measured on January 19, 2018 after the Red Hill Shaft had been pumping at the maximum sustainable rate for about 4 days (Figure 6-9 of DON, 2018a).

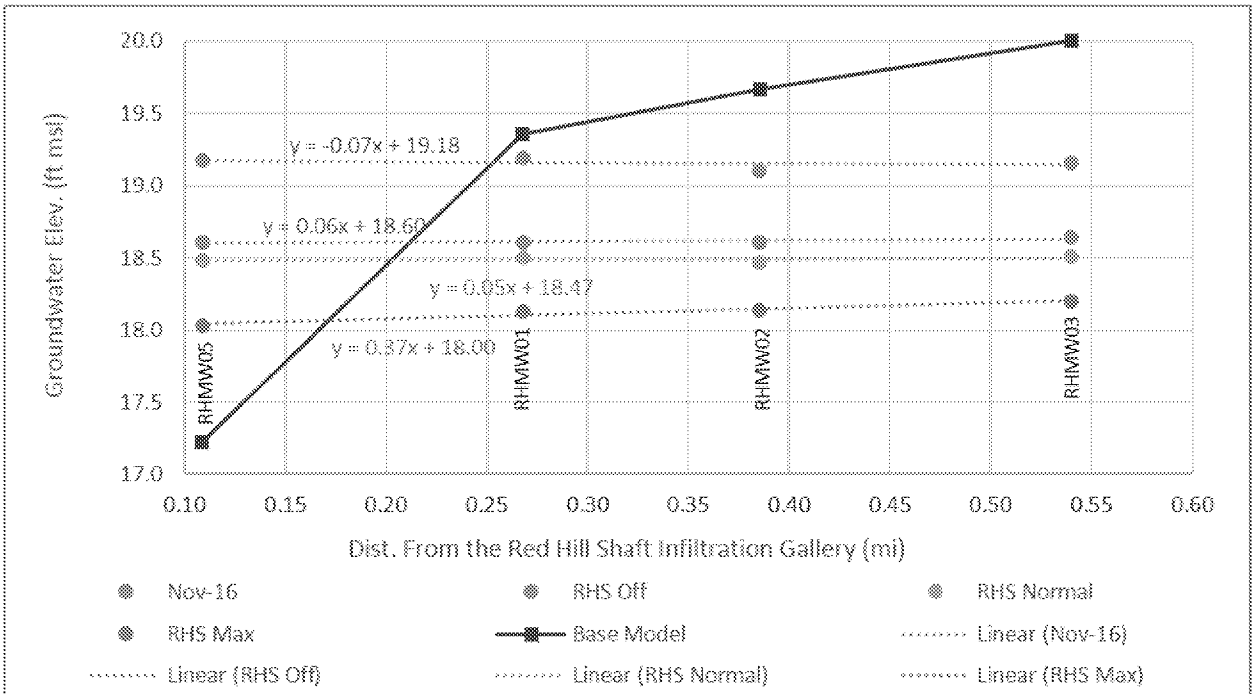

Figure 2. A graph of groundwater elevations in the monitoring wells aligned with the axis of the Red Hill Ridge versus distance from the east end of the Red Hill Shaft infiltration gallery. Pumping conditions shown are: 1) the Red Hill Shaft at minimal pumping for about six months (blue); Red Hill Shaft off for five days (orange); Red Hill Shaft pumping an average rate (gray); Red Hill Shaft pumping at a maximum sustainable rate (green); and water levels simulated by the Base Model (violet).

A best fit trend line and equation is included for each pumping condition, where the x scalar value is the groundwater gradient in ft/mi going down the axis of the Red Hill Ridge. A positive x-scalar indicates a gradient in the mauka to makai direction, while a negative x-scalar indicates a gradient in makai to mauka direction or going inland. The x-scalar for the "Nov-16" data set indicates a makai to mauka or inland gradient. The differences in groundwater elevations are so small that the inferred inland gradient must be viewed with caution. Nonetheless, a very small to negative gradient is a strong indicator that there is little to no natural groundwater flow going down the axis of the Red Hill Ridge when the Red Hill Shaft pumps are not operating. The "RHS OFF" and "RHS Normal" pumping condition data sets both show a very weak mauka to makai gradient with very little difference between the relative water level elevations for two very different pumping conditions. Only when the Red Hill Shaft is pumped at the maximum sustainable capacity is there a definitive mauka to makai gradient. The southwest gradient is still much less than expected suggesting that the majority of groundwater flow is not in that direction. Even then, that gradient is very small at 0.4 ft/mi. These evaluations show that the currently modeled conditions are strongly divergent from those observed.

The typical groundwater gradient toward a pumping center on the Hawaiian Islands is about a foot per mile for the basal aquifers (Oki, 2005; Lau and Mink, 2006). Measured gradients down the axis of the Red Hill Ridge are much smaller than that value (maximum of 0.4 ft/mi when the Red Hill Shaft is pumping at its maximum sustainable capacity). For comparison, Figure 2 shows the water level elevations simulated by the Navy's Red Hill base groundwater flow model reflecting average 2017 groundwater flow conditions (DON, 2018b) and those measured when the Red Hill Shaft and the Halawa Shaft are pumping at their normal rates. The base groundwater model shows a difference of nearly three feet between the groundwater elevation in RHMW03 and RHMW05, which is a 2-well gradient of more than six ft/mi compared to the measured gradient in this direction of 0.05 ft/mi. The variance between modeled and measured is not within a reasonable range of error. What the model accurately portrays is the groundwater gradient that would be measured if the Navy's conceptual model of groundwater flow is reasonably correct, and if other parameters such as recharge and the selected hydraulic conductivity are also reasonably correct. Recharge is based on that of Engott (2016), representing the best estimate of recharge available. The selected hydraulic conductivity of 2,000 ft/day is a value that produces good agreement between the modeled and measured water level response to changes in pumping rate at the Red Hill Shaft, increasing the confidence in the selected value for this parameter. DOH's conclusion is that the Base Model results show that the Navy's conceptual model of groundwater flow needs significant revision.

DOH acknowledges that the presently simulated mauka to makai gradient is consistent with other modeling studies that also assumed mauka to makai flow in the Red Hill area (Rotzoll and El-Kadi, 2007; Oki, 1998; and Todd Engineers, 2006). However, since these studies were done, new and substantially refined data have been collected showing little to no groundwater gradient down the axis of the Red Hill Ridge. In other words, the updates to the available data should update and inform the CSM and groundwater model, but do not appear to substantively do so. The discrepancies between modeled and observed data suggest the CSM and groundwater models do not represent the true directions of flow and contaminant transport. As important, the CSM and groundwater models are non-conservative in their representations of that probable flow and transport. The regulatory agencies recognize that some of the deficiencies noted here may already be addressed in model updates that we have not yet reviewed and welcome those from the Navy team.

Evidence Provided by the Navy to Support Groundwater Flow Aligned With the Axis of the Red Hill Ridge

The Navy presents six primary lines of evidence supporting groundwater flow down the axis of the Red Hill Ridge. These lines of evidence (LOE), from the Red Hill CSM report (DON, 2018a) Section 6.8 Assessment of LOEs for Groundwater Flow are summarized below. Also, based on the presentations by the Navy in March 2019, it is DOH's understanding the Navy remains confident in these LOEs.

1) *Groundwater levels measured throughout the Facility area of interest are consistent with the regional groundwater levels and flow directions reported in previous studies, which include those by the USGS (Oki 2005) and DON (2007, 2010).*
2) *Spatial distributions of groundwater level elevations measured in the Red Hill area monitoring wells show hydraulic gradients are generally southwestward beneath the Facility, even when the Red Hill Shaft was not pumping in November 2016. However, the gradient at Red Hill is extremely gentle and is also affected by local heterogeneities.*
3) *Borehole geologic logs show a deep saprolite zone occurs beneath South Hālawa Valley that forms a low-permeability barrier to groundwater flow. At the new monitoring well RHMW11, the saprolite extends to approximately 87 ft below the regional basal groundwater table. New data from multiple intervals in RHMW11 show the saprolite zone is continuously saturated and the groundwater levels in the saprolite are still equilibrating, but indicate a downward vertical hydraulic gradient, and the water table is much higher than at the nearby well RHMW07 and other Red Hill wells. However, the lateral and vertical extent of the saprolite has not been delineated particularly in the upper portion of South Hālawa Valley.*
4) *Groundwater flows from areas of higher recharge to areas lower recharge or discharge. Recharge occurs as a result of direct infiltration of rainfall, seepage from streams and other water sources at the land surface. Recharge rates are spatially distributed throughout the groundwater model area such that higher recharge occurs at higher land surface elevations as recently estimated by the USGS.*
5) *Water sources in the Hālawa Quarry/cement plant area north of South Hālawa Valley as well as other local recharge sources may increase groundwater recharge rates locally, create shallow perched water zones and increase the water table elevation in the basal aquifer in the area north of South Hālawa Valley.*
6) *Trends in major chemical components in groundwater from monitor wells indicates mixing of two main groundwater types, a sodium-chloride type water from the area north of South Hālawa Valley and sodium-bicarbonate type from the southeast. Groundwater chemistry data from Red Hill area wells compiled and evaluated by University of Hawaii at Manoa (UHM), which include major ions and stable isotopes of oxygen and hydrogen, support the conceptual model of the groundwater recharge and flow pattern in the Red Hill Facility area described above.*

While some of these LOEs may be technically correct as an individual observation, others are incorrect, and collectively the LOEs do not constrain that presumed flow path down Red Hill Ridge.

As discussed above, DOH does acknowledge that the majority of existing groundwater studies did conclude that groundwater flows down the inter-valley ridges to coastal and submarine discharge zones. However, it is not a unanimous consensus and notable hydrogeologists have questioned this prevailing conceptual model of groundwater flow. Below is a discussion of the views and conclusions of three respected hydrogeologists.

The prevailing conceptual model of groundwater flow in southeast Oahu is that described by Hunt (1996). In this conceptual model, groundwater flows from the area of high recharge, in the upper elevations of the Koolau Ridge line, downslope toward coastal and submarine discharge areas. Stream valleys with deep sequences of alluvium and saprolite segregate the flow systems between the valleys into semi-independent aquifer systems. Hunt's conceptual model of groundwater flow in the Red Hill area is stated on pages B36 and B37 of Hunt (1996) as provided below.

> *The Pearl Harbor, Moanalua, Kalihi, Beretania, and Kaimuki ground-water areas of southern Oahu (fig. 12B) are separated by valley-fill geohydrologic barriers (fig. 12C). As in north-central Oahu, the effectiveness of the barriers may diminish inland from the coast with increasing altitude and decreasing penetration of the valleys into the underlying basalt. The boundary between the Pearl Harbor and Moanalua areas has been revised from South Halawa Valley to North Halawa Valley (fig. 5) following Eyre (P.R. Eyre, U.S. Geological Survey, written commun., 1991). Eyre reasoned that North Halawa Valley is deeper than South Halawa Valley and, therefore, is a more appropriate boundary between the two areas. This interpretation is consistent with Wentworth (1951). The curved trend of this barrier reflects an assumed paleodrainage pattern in southern Oahu before island subsidence and sediment infilling of the valleys. The Kaimuki area is bounded on the east by the Kaau rift zone and, perhaps, by valley fill in Palolo Valley (fig. 5).*

This conceptual model has been used by Oki (1998, 2005), Whittier et al., (2004), Rotzoll and El-Kadi (2007) and others the Navy has cited.

One critical parameter needed to evaluate groundwater flow in the Moanalua/Red Hill/Halawa region is the degree to which the valley fill/saprolite sequence extends downward into the groundwater aquifer. As described above, Hunt (1996) does not provide any analysis of the location where the incision of the valley fill and saprolite rise above the depth of the fresh/saltwater transition zone or the top of the groundwater table.

Prior analyses of the hydrology of east Oahu, by Wentworth (1942) and Mink (1980) recognized that water levels drop about one foot at each aquifer system boundary as one progresses from the Nuuanu Aquifer System to the Waimalu Aquifer Sector (Mink and Lau, 1990). They also documented an unusually flat water table gradient within each aquifer system, from Nuuanu to and including the Moanalua Aquifer Systems with each showing very small mauka to makai (mountain to sea) gradients and both postulated that groundwater flow occurs between the currently delineated aquifer systems that Hunt's (1996) conceptual model proposes as semi-independent. Wentworth (1942) produced two possible conceptualizations of the depths to which the valley fill/saprolite sequences intrude into the basal groundwater in the North and South Halawa Valleys. These conceptualizations, shown in Figure 3, below were based on projecting the valley slopes downward and constraining the shallowest (Conceptualization A in Figure 3) and the deepest (Conceptualization B in Figure 3) downward extent of the valley fill/saprolite sequence. Conceptualization A only penetrates to the top of the water table in North and South Halawa Valley, whereas Conceptualization B extended the barrier downward to -100 ft msl (South Halawa Valley) and -120 ft msl (North Halawa Valley). In Wentworth's conceptualizations, the shallowest depth of the Moanalua valley fill/saprolite sequence was about -40 ft msl (A) and the deepest about -380 ft msl (B). The cross-section shown in Wentworth's Figure 25 is defined by a line tangent to the 500 ft contour loops on ridge spur facets. This cross-section line is approximated in Figure 1.

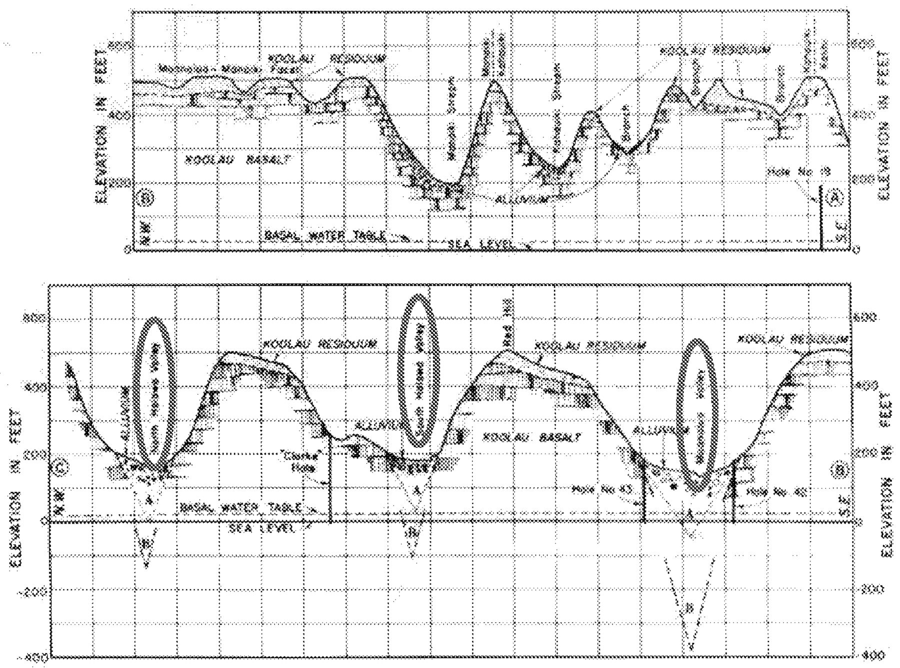

Figure 25 - Geologic cross-section from Kalihi to Aiea, along a line tangent to the several 500 foot contour loops on the spur facets. The several drill holes indicated are not on this line but each is projected into this cross-section in a position corresponding closely with its relation to the valley and the valley wall. The basal water table from Kalihi to the east side of Moanalua approximates the elevation of 24 feet (October, 1940); on the west side of Moanalua Valley is a drop of about 0.70 feet, then one to 21.7 west of South Halawa and to 19.80 west of North Halawa Valley. No drill holes have explored the deeper parts of any of these valleys and possible rock profiles A and B are based on width and steepness of valley topography. Profile A is about the shallowest that seems plausible; profile B is no deeper than is possible if rock walls continue as steep as some revealed in Palolo Valley by drilling.

Figure 3. This figure extracted from Wentworth (1942) shows two potential depths of the valley fill/basalt contact for the Halawa and Moanalua Valleys. Trace of cross-section is shown in Figure 1

In a report to HBWS, Mink (1980), postulated that there was very little resistance to groundwater flow from Moanalua (zone 4) to Halawa (zone 6) and stated that:

> *"The basal groundwater resources of the Honolulu District traditionally have been treated as separate from the Pearl Harbor aquifer even though flow from the Moanalua region, Area 4 of Board of Water Supply terminology, freely moves into the Halawa region, the start of Area 6.....*
>
> *The Honolulu subregions have been called "isopiestic areas" because heads apparently are identical within each subregion (i.e. Aquifer Systems) (the word "isopotential" would have been more appropriate than isopiestic). If indeed the heads were identical over a region, groundwater would not flow, an impossible situation given that inflow to the aquifers must be balanced by outflow. Actually, throughout the Honolulu District groundwater flows northwestward along a gradient of one foot to the mile. The equipotentials generally are aligned at right angles to the trace of the caprock, curving to be continuous with those in the Pearl Harbor region west of Moanalua (see equipotential maps).*
>
> *The groundwater of the Honolulu District that is not extracted by pumps or does not leak into the caprock flows toward the Pearl Harbor springs. At the high original heads, leakage in Honolulu was principally at the inner thin edge of the caprock; as the heads were reduced by pumping, this leakage diminished, though even today it persists. Probably very little leakage penetrates the*

> *clays and compacted terrestrial alluvium at the base of the thicker part of the caprock wedge. The residual flow from Area 4 toward the springs (*i.e. Kalalaou Springs*) is on the order of 10 to 15 mgd under current development practices. Except perhaps for the short interval when Shaft 12 (Halawa) and Shaft 11 (Red Hill) were being dewatered during excavation, the groundwater flow gradient has always been from the Honolulu District toward Pearl Harbor."*

It has not been conclusively determined which of the conceptual models (Hunt [1996] or the Wentworth (1942)/Mink [1980] models) of groundwater flow in the Moanalua/Red Hill/Halawa region best represents actual conditions in this region. However, it is DOH's conclusion that the newly acquired groundwater gradient data are most consistent with Mink's conceptual model.

The increased data quality, density and synoptic scope collected as part of the Red Hill groundwater investigation was not available to these hydrogeologists when they published their studies. These new data do not indicate a groundwater gradient down the Red Hill Ridge that is consistent with that put forth by some of the previous studies. What the data do show is that no down-ridge gradient existed at the end of a prolonged period of very little pumping at the Red Hill Shaft and only a minimal gradient in that direction when the Red Hill Shaft is pumping at a normal rate. As the discussion of Mink (1980) shows, the groundwater elevations decrease significantly going in a northwest direction from the Honolulu Aquifer to the Pearl Harbor Aquifer. Based on groundwater elevations alone, groundwater flow to the northwest is best supported by the data. However, as noted in LOE No. 2 above, local heterogeneities must also be considered. All of the wells in the Red Hill Groundwater Monitoring Network (RHGWMNW) with the exception of RHMW07, HDMW2253-03, and the saprolite zones of RHMW11 show a high degree of connectivity. The response of water level elevations in these wells to on/off cycles of the Red Hill Shaft is nearly in unison with only a small attenuation and phase shift in the response to changes in pumping stress. This suggests that local heterogeneities likely do not play a significant role in influencing the groundwater gradient across the RHGWMNW with the exceptions previously noted.

The groundwater flow direction will be influenced by the saprolite where it extends beneath the water table. That influence will increase from negligible at the point where the saprolite/basalt interface just reaches the water table, to approximating a low-flow barrier where the saprolite extends down to the mid-point of the freshwater/saltwater transition zone. As will be discussed later, it is DOH's view that the Navy is over-estimating the resistance that the saprolite poses to northwest groundwater flow by over estimating the up-valley extent and the depth penetration into the aquifer.

DOH concurs that the high elevation recharge areas are the primary source of groundwater to the basal aquifers and that groundwater not extracted by pumping or discharging to surface water will enter the coastal waters. However, that path is not always simply mauka to makai. Groundwater flows from areas of higher potential (higher groundwater elevation relative to sea level) to areas of lower potential when and where hydraulic conductivity is sufficient to allow flow. There is no requirement for groundwater to take the straightest path in a mauka to makai flow direction: water will flow along the trajectory where the aggregate resistance to flow is lowest. For example, the Lahaina Groundwater Tracer Study (Glenn et al., 2013) found that the groundwater flow path was offset about 70 degrees from the most direct path between the wastewater injection wells and the coast.

The Navy has postulated that operations at the Halawa Quarry results in a groundwater mound that creates a hydraulic barrier between the Facility and the north side of North Halawa Valley. However, no quantitative evidence has been presented support this hypothesis and other considerations suggest that the quarry operations do not create a significant hydraulic barrier. Section 5.1.4.4 of the CSM (DON, 2018a) gives the dimensions of the Quarry collection basin as 500 ft by 1,200 ft. Assuming that rainfall in the area is 100 inches per year, this hypothetical recharge results in an infiltration rate of about a 100,000 gallons per day infiltration rate. This does seem substantial. However, it is equivalent to an injection rate of about 70 gpm that pumping tests show results in minimal changes in the groundwater elevation.

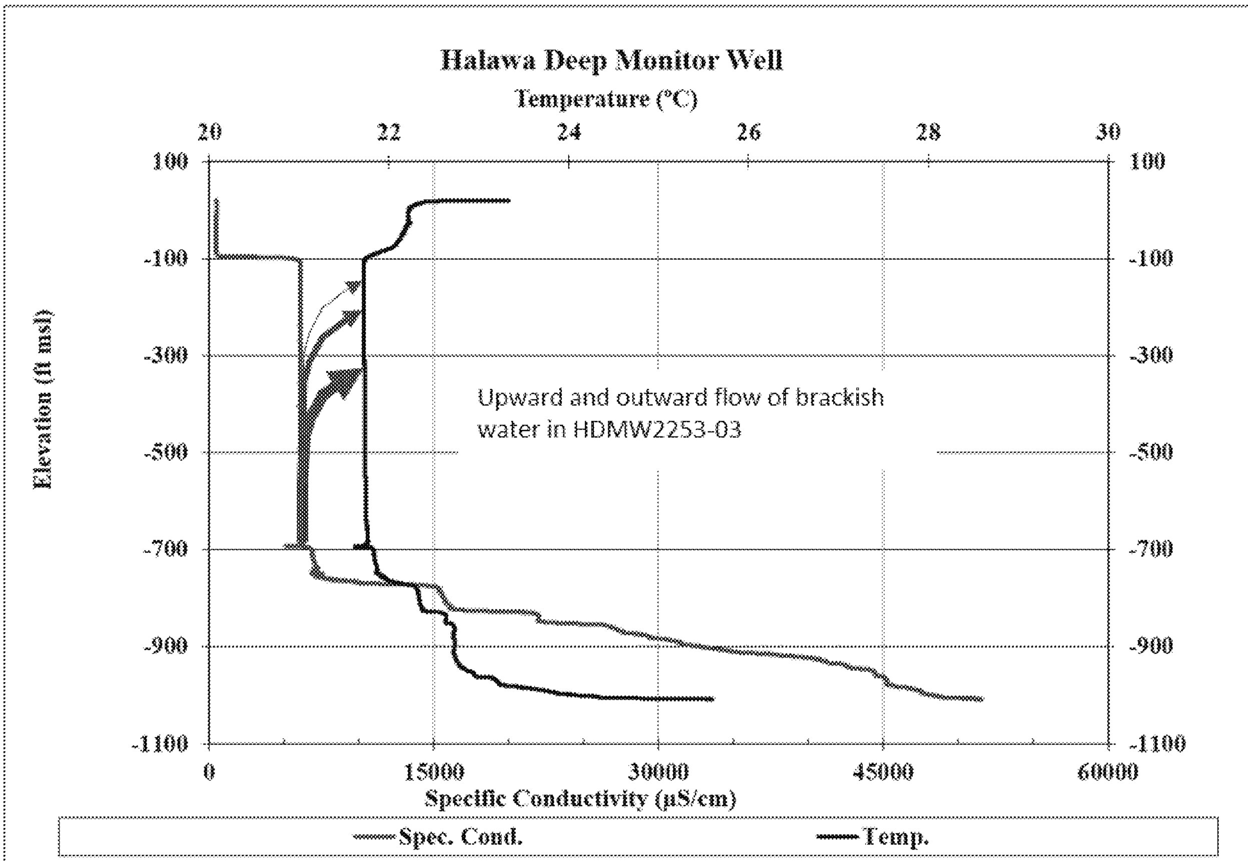

Figure 4. A conductivity-temperature-depth profile of HDMW2253-03, and a conceptualization of the upward and outward flow of brackish water into the formation. The water in the wellbore abruptly shifts from brackish to fresh at -100 ft msl

In LOE No. 6, the Navy proposes that a sodium-chloride type water from north of South Halawa Valley is mixing with a sodium-bicarbonate type water from the southeast. The Navy hypothesizes that water from the brackish zone of HDMW2253-03 is influencing the chemistry of RHMW06 and RHMW07 showing that groundwater flows from north of South Halawa Valley to these wells (DON, 2018a, Section 6.7). Figure 4 shows a conductivity-temperature-depth profile for HDMW2253-03 and a conceptualization of flow within the wellbore based on this profile and the borehole video presented to the AOC parties in March 2019. This video is held by the Commission on Water Resources Management and arrangements to view this video can be made with this agency. The groundwater within the wellbore of HDMW2253-03 shifts abruptly from brackish to fresh at -100 ft msl. For the Navy to support their hypothesis that the saltiness of RHMW06 and RHMW07 is due to the up flow of brackish water from HDMW2253-03 they need to explain how cooler denser water can pass beneath the hypothesized saprolite barrier and rise from -100 ft msl to about 15 ft msl and warm significantly in the process. It seems much easier to reconcile the saltiness of RHMW06 and RHMW07 with the warm brackish water in Oily Waste Disposal Basin (OWDB). As stated in the Navy's hypothesis the sodium-chloride type water from north of South Halawa Valley mixes with sodium-bicarbonate type water from the southeast. This would infer an inflow of groundwater from the southeast, not from the northeast and is inconsistent with the Navy's conceptual model of groundwater flow from the northeast to the southwest.

The Navy also used groundwater chemistry data provided and evaluated by the UHM to support its conclusions. In contrast to what the Navy team concluded, UHM stated in their interpretations inclusive to these data that neither mauka to makai nor cross-ridge flow could be supported by the chemistry results provided. UHM further stressed when delivering the geochemical data to the Navy that the great chemical variability within the RHGWMNW was as great or in some cases greater than that in USGS 2004 NAWQA Study (Hunt, 2004), which sampled all of central Oahu and the Honolulu Aquifer. It was further suggested that this variability indicated a degree of compartmentalization of the groundwater within the Red Hill system.

In summary, the Navy's CSM states that groundwater beneath the facility originates in the high elevation recharge areas and flows directly downslope through the facility to coastal and discharge zones. This mauka to makai flow is augmented by up flow through HDMW2253-03 and focused recharge at the Quarry significantly altering the chemistry of wells along the northwest Red Hill Facility boundary. This conceptual model does not conform to the data. With the exception of RHMW04, the chloride concentrations in the northwest boundary wells are an order of magnitude greater than that in upper tunnel wells (RHMW02 & 03). The Navy's CSM requires a significant flux of groundwater from HDMW2253-03 and the Quarry to account for the salinity in the northwest boundary wells. This doesn't seem to be occurring. The Navy's CSM also fails to account for the increase in salinity going from the northeast to the southwest.

The wide variability in groundwater chemistry and the flat gradient could be more easily explained by much less groundwater flowing beneath the Facility. Much lower inputs of chemically contrasting groundwater would be required to attain the span of chemistry we observe. Regarding the elevated salinity in RHMW06 & 07, it is interesting to note that in the 2000 investigation of the OWDB a groundwater flow direction was measured from OWDB wells toward RHMW06 & 07 (Figure 11, DON, 2000). High salinity was measured in two out of three basal wells installed in the OWDB providing a source of salts to RHMW06 & 07. It seems this flow path is more consistent with the available data than that proposed by the Navy.

Data Supporting Groundwater Flow to the Northwest

Regional Groundwater Gradients

When evaluating groundwater flow directions, the most common first step is to create contours of the groundwater elevation if sufficient data exist. Using data from the Red Hill CSM report (DON, 2018a), this study developed regional groundwater contours for two different pumping conditions, the "Halawa Shaft Off" (Figure 5) and "Red Hill and Halawa Shaft Normal" pumping conditions (Figure 6). In an isotropic aquifer (i.e. the hydraulic conductivity does not change with orientation) groundwater flow is perpendicular to groundwater elevation contours. The arrows on these two figures approximate groundwater flow directions using this assumption while recognizing that the Red Hill area is not isotropic (i.e., there are deviations from ideal flow). Wells RHMW07, HDMW2253-03, and Moanalua DH43 were not considered in the contouring due to abnormalities in their groundwater elevations, as the Navy team has also recognized. The "Halawa Shaft Off" pumping condition was selected since it provides an additional static water level data point in the Halawa-Aiea area and is the condition least likely to induce northwesterly groundwater flow. Regionally, the water levels drop about 0.6 ft from the

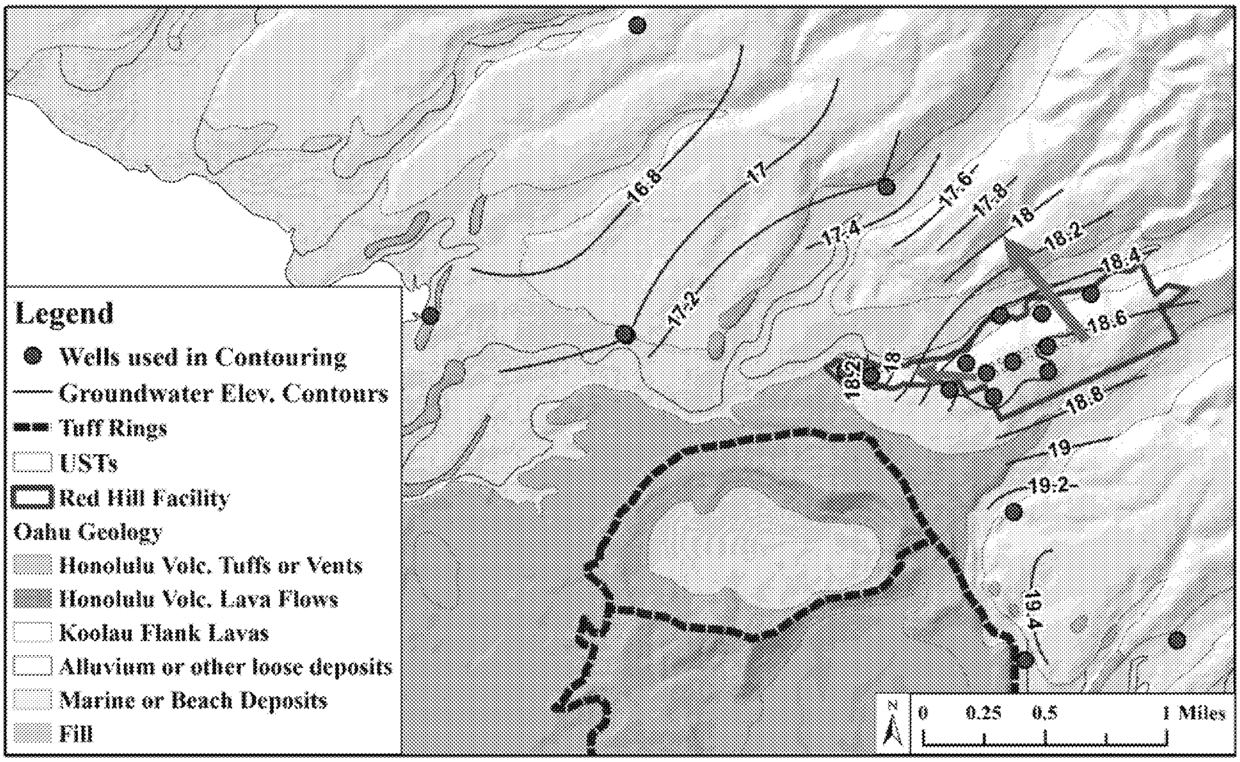

Figure 5. Groundwater elevation contours for the Moanalua/Red Hill/Halawa region when the Red Hill Shaft is pumping at a normal rate and the Halawa Shaft has been off for 9 days. Arrows indicate the implied groundwater flow direction based on the groundwater elevation contours. Data are taken from Figure 6-10 in the Red Hill CSM (DON, 2018a)

Moanalua Ridge to the Red Hill Ridge, then drops an additional 1.4 ft from the Red Hill Ridge to the North side of North Halawa Valley. There are too few points in the Moanalua area to confidently define a groundwater gradient. However, beneath the Red Hill Ridge the groundwater contours generally run parallel to the axis of the ridge down to about RHMW05, then contours are more oblique to the axis of the ridge producing an inferred gradient in a westerly direction. It is also important to note that the highest water levels are in those wells aligned with the axis of the ridge whereas the wells on the flanks of the ridge have slightly lower groundwater elevations. As a group, the wells that are on the northwest flank of the Red Hill Ridge have the lowest groundwater elevations. On the north side of North Halawa Valley in the Halawa-Aiea area the data are sparse, but the northeast to southwest trending groundwater contour pattern continues suggesting groundwater flow to the northwest (i.e. perpendicular to the groundwater elevation contours). The most northwest well is the Kaamilo Deep Monitoring Well. Like HDMW2253-03, the depth versus specific conductivity profile indicates strong intra-borehole flow that could bias the water levels measured in this well. The groundwater elevation contours beneath the Red Hill Ridge and beneath the Halawa-Aiea area indicate that at least where the penetration of the saprolite into aquifer is either shallow or non-existent, the relative groundwater elevations indicate groundwater flow to the northwest. More specifically, the groundwater contouring strongly suggests that the flow direction beneath the upper part of the facility is to the northwest. This observation is in direct contrast to the Navy's expectation that the water flows along the shortest mauka to makai path from the high elevation recharge areas to the coast.

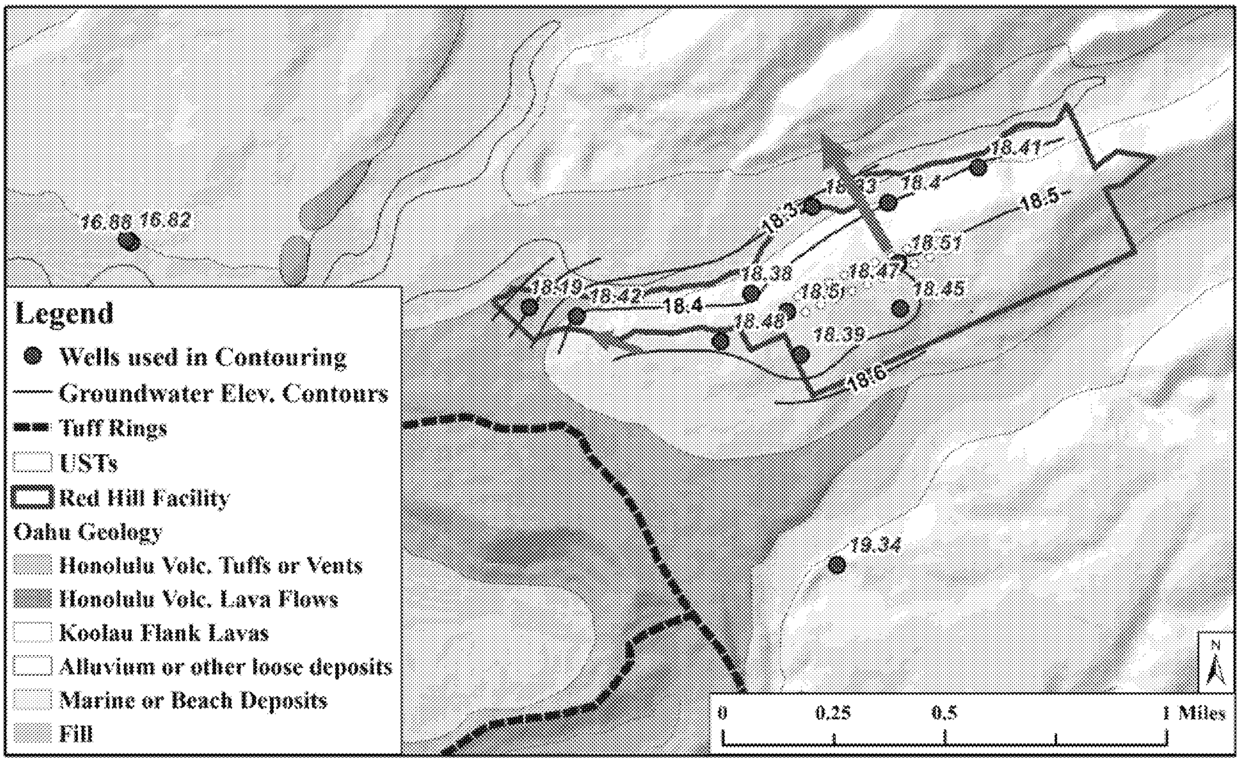

Figure 6. Groundwater elevation contours for the Red Hill Groundwater Monitoring Network when the Red Hill Shaft is pumping at a normal rate. Data based on Figure 6-12 in the Red Hill CSM (DON, 2018a)

Figure 6 shows groundwater contours drawn for the RHGWMNW only and using a 0.1 ft contour interval. The water levels measured at the wells are shown as the red numbers while contour labels are shown as black numbers. This figure represents a condition where the Red Hill and Halawa Shafts are pumping at their normal rates with the data taken from Figure 6-12 of DON 2018a. As with the previous set of contours these trend from northeast to southwest indicating a northwest gradient for groundwater in the upper part of the Facility, beneath the USTs. The northwest gradient indicates the likely direction of groundwater flow in absence of any barrier that resists groundwater flow in that direction.

Valley Fill/Saprolite as a Barrier to Northwest Groundwater Flow

The groundwater elevation data clearly show a groundwater gradient going to the northwest of the Facility. However, groundwater will only flow perpendicular to the groundwater elevation contours in an isotropic and homogeneous aquifer. It is highly unlikely that these two conditions exist in the Moanalua/Red Hill/Halawa region. As described earlier, the prevailing conceptual model of groundwater flow in this area is that the valley fill and underlying saprolite present a low permeability barrier to groundwater flow across valleys. Prior to the Red Hill AOC investigation there was very limited data available as to how deep the valley fill/saprolite sequence extended into the freshwater aquifer beneath the Halawa Valleys. A primary source for this type of data was from the geologic logs of the drill cuttings for HDMW2253-03. Depending on how the geologic logs are interpreted, the boundary between the saprolite/basalt interface could be as shallow as -5 ft msl or as deep as -55 ft msl. Relative to the Facility, a line drawn perpendicular to the axis of South Halawa Valley and through HDMW2253-03 would intersect the Facility tank farm at about Tank 11. That leaves a significant portion of the Facility with no indication of whether or not the valley fill/saprolite sequence serves as an effective barrier to northwest groundwater flow. The two estimated depths of the saprolite/basalt interface at HDMW2253-03 represent an intrusion into the aquifer of 3 to 9 percent. This means that more than 90 percent of the freshwater aquifer thickness is available for water transmission. This assumes that the saprolite/basalt interface encountered by HDMW2253-03 represents the greatest depth of that interface along that transect across the valley. HDMW2253-03 lies very near the center of the valley fill mapped by the USGS (Sherrod et al., 2007), making the above assumption reasonable.

Because the LNAPL density only allows it to be transported at the top of the water table, another critical determination is the point, up-valley, at which the saprolite/basalt interface rises above the water table: below (makai of) this transition point, LNAPL will be intercepted by a low permeability barrier (saprolite), whereas mauka of the transition, it can have a more direct trajectory to the northwest. The Navy has presented two possible locations in South Halawa Valley where this might occur by projecting lines up slope from HDMW2253-03 assuming a 3 percent slope. The starting elevation for the first line was at an elevation of -5 ft msl, the shallowest interpretation of the saprolite/basalt interface in the HDWM2253-03 geologic log. This projected line intersected the water table in South Halawa Valley at a point just up valley from where a cross valley line would intersect Tank 19. When the starting elevation for the projected line was -55 ft msl and this line intersected the water table about 1,600 ft up valley from the first line and well up slope from the USTs.

To better define the geometry, and more importantly the depth of the valley fill/saprolite sequence, the Navy contracted Boise State University to conduct a seismic survey of Halawa and Moanalua Valleys (DON, 2018c). There were two transects across North Halawa Valley and three across South Halawa Valley (DON, 2018c). As part of this groundwater flow path evaluation DOH digitized the seismic transects including the depth of the estimated saprolite/basalt interface. We estimated the bottom surface of the saprolite/basalt interface by generating connecting arcs between adjacent transects. Arcs were then projected up valley based on the slope of the arcs connecting the seismic transects. For example, in South Halawa Valley, arcs were generated that connected Seismic Transect D up valley to Seismic Transect E. Arcs were then projected upslope from Seismic Transect E based on the slopes of the arcs between Seismic Transects D and E. Table 1 below lists the seismic transects, the deepest depth of the saprolite/basalt interface, the distance between the deepest points of each transect, and the calculated percent slope.

Table 1. *Slope of the saprolite/basalt interface surface between seismic transect lines*

Valley	From	To	Distance (ft)	Saprolite/basalt Interface elevation (ft msl)		Slope (percent)
				Downslope	Upslope	
South Halawa	Transect F	Transect D	1600	-338	-300	2.4
South Halawa	Transect D	Transect E	2090	-300	-110	9.1
North Halawa	Transect A	Transect B	1020	-260	-20	24

Table 1 shows that the slope between Transect F and Transect D in South Halawa Valley is reasonably close to that used by the Navy. However, moving up South Halawa Valley, the slope between Transect D and Transect E is approximately four times steeper than the slope between Transect F and Transect D. The likely explanation for this increase in slope up valley is that the thickness of the valley fill/saprolite sequence decreases as the morphology of the valley shifts from a broad open valley to a V-shaped valley. Within the V-shaped portion of the valleys, the stream is still down-cutting rather than the case of a deeper valley being filled by sediments where the valley is broader. In North Halawa Valley the slope between Transect A and Transect B is even steeper at 24 percent.

The purpose of these geometric projections was to develop a three-dimensional surface of the saprolite/basalt interface. Contour lines were then generated representing the trace of the saprolite/basalt interface at: 1) the water table; and 2) at a depths of 10, 25, and 50 percent of the aquifer thickness. The results of these evaluations are shown in Figure 7. The saprolite/basalt interface of this evaluation is consistent with the most down valley point estimated by the Navy and roughly adjacent to the Tank 19. The point at which the saprolite/basalt interface reaches a 25 percent of the aquifer thickness does not occur until a point roughly adjacent to Tank 1. It is important to note that this evaluation used the deepest estimated depth of the saprolite/basalt interface at HDMW2253-03, yet using the saprolite/basalt interface slope calculated from the seismic data rather than using a literature value, the point at which this interface rises above the water table was very close to what the Navy estimated using the shallowest saprolite/basalt interface depth at this well. In North Halawa Valley, the deepest saprolite/Basalt interface depth estimated by seismic survey at Transect B was -20 ft msl. Projecting up North Halawa Valley the saprolite/basalt interface is estimated to rise above the water table slightly before the Halawa Shaft.

The important conclusion of this saprolite/basalt interface depth evaluation is that the resistance to northwest groundwater flow posed by the valley fill/saprolite sequence is likely over-estimated by the Navy's current conceptual model. Extrapolations based on the seismic study indicates that the valley fill/saprolite sequence likely poses little resistance to groundwater flow in the South Halawa Valley adjacent to the USTs and in North Halawa valley adjacent to the Halawa Shaft. As Figure 7 shows, the aquifer penetration of the valley fill/saprolite sequence in South Halawa Valley is less than 50 percent for nearly the entire length of this valley that is adjacent to the Facility. This is concerning since the 2015 and the 2017-2018 Synoptic Water Level Studies show that groundwater elevation at RHMW04 is about a foot higher than at the Halawa Shaft; and the groundwater elevation at OWDF-MW1 is 1.5 ft higher than at HBWS observation well T-45. With this difference in head across Halawa Valley and the limited saprolite penetration, groundwater almost certainly flows from Red Hill beneath and around the valley fill/saprolite sequence to the Halawa side of North Halawa Valley.

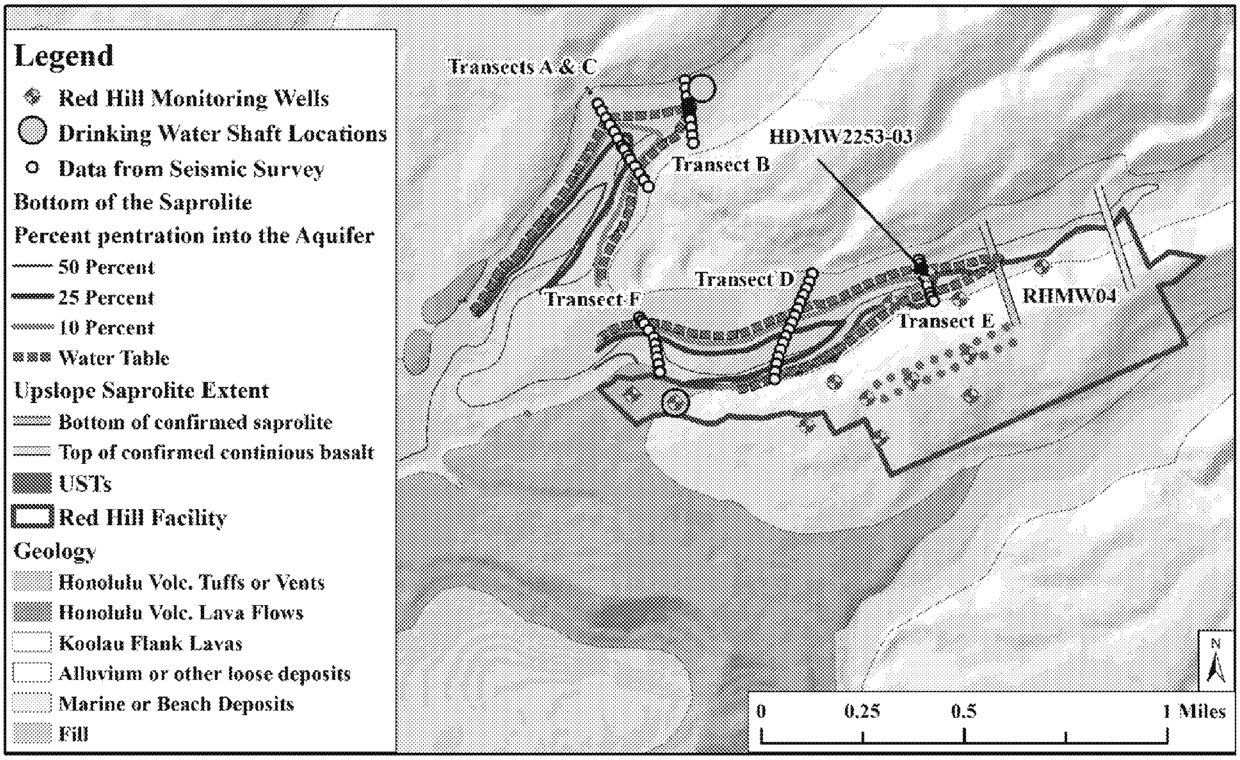

Figure 7. Estimated depth to which the saprolite extends into the freshwater aquifer expressed as the percent of total aquifer thickness penetrated by the saprolite.

As noted in Section 6.1.4 of the CSM report (DON, 2018a), the hydraulic head in the basalt zones of RHMW11 generally define a downward gradient. This is consistent and would be expected for groundwater flowing to the northwest by passing under the saprolite/basalt interface. Figure 6-10 of the CSM report (DON, 2018a) shows that the groundwater elevation in RHMW11-Zone 5 is more than a foot higher than that at the Halawa Shaft when the pumps are off. As Figure 7 shows, the saprolite between RHMW11 and the Halawa Shaft extends much less than 25 percent into the aquifer, making well over 80 percent of the aquifer thickness available to transmit water from the Red Hill side of South Halawa Valley to the north side of North Halawa Valley.

Capture Zone Assessments

The next important step is using knowledge of groundwater flow patterns to develop release response plans. A critical question that needs to be answered when developing a release response plan is, "What is the relationship between groundwater flow and the groundwater captured by the Red Hill Shaft?" A groundwater gradient toward the Red Hill Shaft must have sufficient magnitude to move groundwater and contamination in that direction. Furthermore, a capture zone of sufficient width is required to balance inflow in the Red Hill Shaft infiltration gallery against the out flow from the pumps. In the absence of a sufficient gradient, other contaminant pathways must be considered, and alternative methods of plume capture developed.

The capture zones delineated by the Navy for drinking water sources near the Facility and as presented in the Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (DON, 2018b) Appendix A are dependent on the modeled groundwater gradient being correct. The capture zones were delineated based on the trajectory of virtual particles within the modeled groundwater flow field. The groundwater flow field is determined by the modeled groundwater gradient. As shown in Figure 2, the model groundwater gradient bears very little resemblance to the measured gradient. Since the model does not accurately replicate the groundwater gradient the capture zones for the Red Hill Shaft, and also the Halawa Shaft remain un-delineated. To revise the groundwater model to produce gradients that result in defensible capture zone delineations may require a re-evaluation of the model boundary conditions or the hydraulic parameter values used for the non-basalt geology in the model. The selected values for the basalt hydraulic conductivity and effective porosity do not need significant revision since the simulated aquifer response to Red Hill Shaft pumping and non-pumping cycles was similar to that measured by the synoptic water level monitoring. This leaves changing other model inputs such as the boundary conditions to produce defensible hydraulic gradients upon which to delineate capture zones.

Summary and Conclusions

A groundwater model relies on a multitude of parameters such as hydraulic conductivity, recharge rates and distribution, and groundwater fluxes across model boundaries. Since the values of nearly all of the parameters are arrived at indirectly, critiquing the model by way of a directly measurable parameter is critical. In the Moanalua/Red Hill/Halawa region the spatial distribution of water levels and the magnitude of water level response to changes in pumping rates/scenarios are the only measurable parameters available for assessing the model reliability. The Navy's transient model simulations do a good job of replicating the monitoring well responses to changes in pumping rates at the Red Hill Shaft. This agreement between the modeled and measured data provides confidence that the chosen hydraulic conductivity and effective porosity for the basalt aquifer are reasonably accurate. What the groundwater flow model does very poorly is replicating the relative groundwater elevations within the RHGWMNW, indicating deficiencies in the choice of boundary conditions or values, or the hydraulic conductivity assigned to the non-basalt geologic units. This lack of agreement between the modeled and measured groundwater elevations, particularly at the magnitude of contrasts noted above, suggests that the groundwater model will not reliably reflect groundwater flow, contaminant transport, plume capture or other key risk-based considerations. Aside from the reliability aspects, the CSM and the associated groundwater model suggest non-conservative outcomes and purport the system to be more protective of groundwater resources than is suggested by the data noted above.

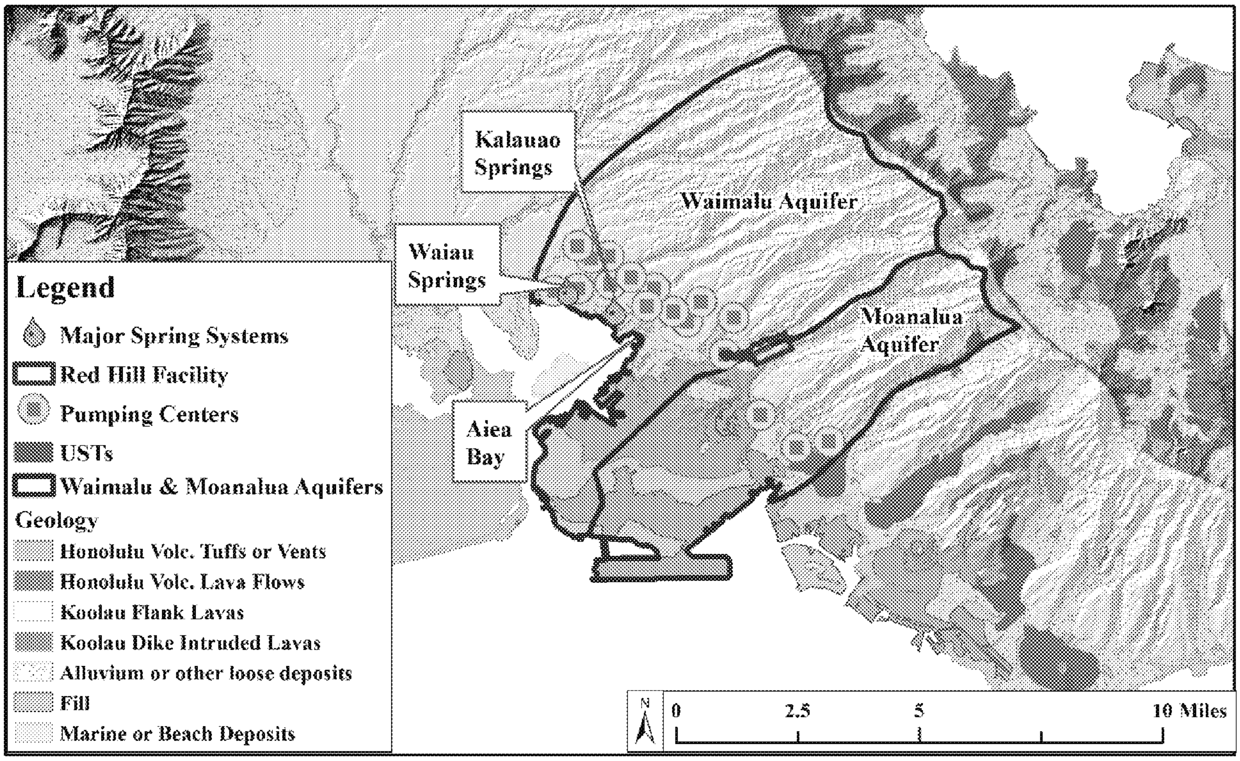

Figure 8. The regional geology of the southeast Oahu showing the major pumping centers in the Moanalua and Waimalu Aquifers and the major spring systems in these same aquifers.

A plausible interpretation of the geologic and hydrologic observations noted above is that low permeability structures between the Facility USTs and the shoreline divert groundwater flow from beneath the Facility to the eastern part of the Pearl Harbor Aquifer where there are a significant number of groundwater sinks. Figure 8 shows the major pumping centers and spring systems in the Moanalua and Waimalu Aquifer Systems. There are several major groundwater withdrawals from the Waimalu Aquifer Systems in the eastern part of the Pearl Harbor Aquifer Sector including the Halawa Shaft, just across Halawa Valley from the Facility. Also located in the Waimalu Aquifer Systems are the Kalauao Springs at Pearl Ridge and the Waiau Springs at Pearl City that are major discharge points for groundwater. While the groundwater flow patterns in the Moanalua/Red Hill/Halawa region are poorly understood, a conceptual model that incorporates the subsurface geology of the Honolulu Volcanics in the area diverting groundwater flow toward the northwest is certainly consistent with data that has been collected in last few years.

DOH places a very high value on correctly characterizing the groundwater flow patterns in the Moanalua, Red Hill, and Halawa regions. However, it is critical to note that at this point DOH has not developed an opinion on the degree of risk that operations at the Facility pose to the Halawa Shaft. We are seeking alignment between what the groundwater observation data indicate and what the CSM and groundwater flow model indicate as only westerly flow. This alignment is a critical step in objectively assessing the contaminant transport and associated risks the Facility may pose to public drinking water sources.

References

DON. 2000. Remedial Investigation Phase II – Red Hill Oily Waste Disposal Facility, Halawa, Oahu, Hawaii – Volume I, Technical Report. Prepared by EarthTech, September 2000

DON. 2007. Red Hill Bulk Fuel Storage Facility Final Technical Report – Pearl Harbor, Hawaii. Prepared for Department of the Navy, Commander, Naval Facilities Engineering Command, Pacific, Pearl Harbor, Hi. Prepared By TEC, Inc. August 2007

DON. 2010. Final Summary Report – Red Hill Fuel Storage Facility, Oahu, Pearl Harbor. Prepared for Commander, Navy Region Hawaii, Environmental Department Code N45. Prepared by TEC, Inc. August, 2010

DON. 2018a. Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, O'ahu, Hawai'i. Prepared for the Defense Logistics Agency Energy. Prepared by AECOM Technical Services, Inc. July, 2018

DON. 2018b. Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, Oahu, Hawaii. Prepared for the Defense Logistics Agency Energy. Prepared by AECOM Technical Services, Inc. July, 2018

DON. 2018c. Seismic Profiling to Map Hydrostratigraphy in the Red Hill Area – Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, Oahu, Hawaii. Prepared for the Defense Logistics Agency Energy. Prepared by L. Liberty and J.S. St. Clair of Dept. of Geosciences, Boise State University, Boise, Idaho. March, 2018

Glenn, C.R., Whittier, R.B., Dailer, M.L., Dulaiova, H., El-Kadi, A.I., Fackrell, J., Kelly, J.L., Waters, C.A., and J. Sevadjian, 2013. Lahaina Groundwater Tracer Study er Study a Maui, Hawaii, Final Report, prepared for the State of Hawaii Department of Health, the U.S. Environmental Protection Agency, and the U.S. Army Engineer Research and Development Center

Hunt, C.D. 1996. Geohydrology of the Island of Oahu, Hawaii. U.S. Geological Survey Professional Paper 1412-B. 63 p.

Hunt, C.D. 2004. Ground-Water Quality and its Relation to Land Use on Oahu, Hawaii, 2000-01. U.S. Geological Survey Water Resources Investigations Report 03-4305. 57 p.

Lau, S.L., and Mink, J.F. 2006. Hydrology of the Hawaiian Islands. University of Hawaii Press, Honolulu, Hawaii. pg. 137

Mink, J.F. 1980. The State of the Groundwater Resources of Southern Oahu. A Report to the Honolulu Board of Water Supply. 83 p.

Mink, J.F and Lau, L.S. 1990a. Aquifer Identification and Classification for Oahu: Groundwater Protection Strategy for Hawai'i, Technical Report No. 179, Water Resources Research Center, University of Hawai'i at Manoa https://scholarspace.manoa.hawaii.edu/handle/10125/1961

Oki, D.S. 1998. Geohydrology of the Central Oahu, Hawaii, Ground-Water Flow System and Numerical Simulation of the Effects of Additional Pumping. U.S. Geological Survey Water-Resources Investigation Report 96-4267. 142 p.

Oki, D.S., 2005, Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii: U.S. Geological Survey Scientific Investigations Report 2005-5253, 111 p.

Rotzoll, K., and El-Kadi, A.I. 2007. Numerical Ground-Water Flow Simulation for Red Hill Fuel Storage Facilities, NAVFAC Pacific, Oahu, Hawaii. Prepared for TEC, Inc. Prepared by Water Resources Research Center, University of Hawaii. August, 2007

Todd Engineers and ETIC Engineering. 2005. Final Report – Development of a Groundwater Management Model, Honolulu Area of the Southern Oahu Groundwater System. Prepared for the Honolulu Board of Water Supply. October, 2005

Wentworth, C.K. 1942. Geology and Ground-Water Resources of the Moanalua-Halawa District. Prepared for the Board of Water Supply, Honolulu. Figure 25

Whittier, R.B., K. Rotzoll, S. Dhal, A.I. El-Kadi, C. Ray, G. Chen, and D. Chang, 2004. Hawaii Source Water Assessment Program Report. Hawaii Dept. of Health County of Honolulu, 103 pp